A Magnetic Tape Recorder for Long Operating Life in Space

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In the past, magnetic tape recorders for space applications have caused many problems. However, they are still widely used because they are the only mass memory device acceptable for spacecraft. Most of the tape recorder problems have been associated with the mechanical tape transport, while the tape recorder electronics generally achieved a satisfactory performance record. This article describes a tape recorder which uses a very simple mechanical system to transport the tape with very few possible failure modes. The simplicity of the tape transport has been achieved at the expense of added complexity of the electronic system. The resulting tape recorder is better balanced in its mechanical and electronic reliability. The test results with a feasibility model have been very encouraging.

Introduction

Outer-planet spacecraft design studies have established the need for large capacity data storage systems with a lifetime of up to 12 yr. An extensive survey of all available mass storage techniques has shown that magnetic tape recording has the highest probability of meeting the requirements of outer-planet missions until 1980. However, spacecraft and satellite tape recorders in the past have achieved a less than satisfactory performance record in spite of considerable efforts in research and development. Even though JPL has never had an inflight tape recorder failure, doubts have been expressed whether the magnetic tape recorder can ever be perfected enough to meet projected outer-planet reliability and life requirements.

A study of tape recorder failure modes in the past revealed that failures within the mechanical transport package outnumbered failures within the electronic system. However, it was not possible to identify a single part or subassembly within the transport package as being particularly failure prone. The presently used tape transports, therefore,

must be regarded as particularly suspect systems having the potential for many different failure modes.

A study of tape transports which have flown on spacecraft and satellites in the past shows that they were all complex devices with many moving parts. The reason for the complexity of the mechanical system is found in the peculiar functional and environmental requirements placed on space-borne data storage systems. One of the requirements most difficult to achieve with a tape recorder is the multiple-data rate. For certain applications in the past, data rates differed by a ratio of nearly 1:2000, which means that the highest tape speed had to be 2000 times faster than the lowest tape speed.

Several years ago JPL recognized the need for less complicated tape transports and directed a strong effort toward the development of simple, reliable tape transports. The first of these transports uses the peripheral drive principle and will be flown for the first time in 1971 on board the *Mariner* spacecraft. This machine has achieved satisfactory test results, and the confidence is high for it to set new standards for tape recorder life and reliability. However, the peripheral drive tape recorder is only one step toward the development of a truly reliable recorder, which will completely satisfy outer-planetary spacecraft requirements until 1985. Several more steps toward achieving this ultimate goal are already taking shape in the laboratory.

This article describes a data storage system utilizing a simple tape transport, of which a feasibility model has already been built. This transport uses only two rotating assemblies. None of the rotating assemblies operate at high speed. Besides the magnetic tape and the two rotating assemblies, there are no other moving parts, such as drive belts or spring tension devices. Most important, however, is the fact that this transport, due to its simplicity, is expected to have very few possible failure modes, and even those should occur with a low probability. The mechanical simplicity is achieved partly by unorthodox methods of driving and tensioning the tape and partly by elimination of the multi-speed requirement from the tape recorder while retaining it for the data storage system as a whole.

The data storage system uses a pair of solid-state buffer memories for data rate conversion. It allows the tape recorder itself to operate at a single data rate which can be selected to be compatible with the tape transport. As a consequence, the mechanical subsystem has been simplified and made more reliable at the expense of additional electronics. The advantages gained for the transport will outweigh the disadvantages caused by the introduction of additional electronics. If redundancy is used for certain circuits, such as the buffer memory, it will be possible

to further increase reliability of the data storage system. Present plans call for this tape recorder to be used for outer-planet missions.

Data Storage System Design

The data storage system will be able to store and reproduce a large amount of digital data at a variety of data rates. Figure 1 shows the data storage system in block diagram form. It uses a single-speed tape recorder and two identical serial buffer memories. The tape recorder communicates only with the buffer memories at a constant data rate, while the buffers communicate with the other subsystems at any data rate up to a certain limit R.

During recording, data is first stored in Buffer A, while Buffer B transfers its contents to the tape recorder at a sufficiently high data rate to assure the data transfer to be finished before Buffer A is filled to capacity. The tape recorder is subsequently stopped until Buffer A is full. Then the function of the two buffers is reversed, and Buffer A transfers its contents to the tape recorder while Buffer B is recording the incoming data stream. This allows the recording of a continuous data stream with a tape recorder operating in a start/stop mode. The switches indicated in Figure 1 represent logic circuits capable of properly directing the data streams and starting and stopping the tape recorder. This data storage system is described in detail in Reference 1.

The buffer memory can be a long shift register or any other semiconductor, core, or plated wire memory. The buffer capacity determines the length of a data block written on the magnetic tape. The tape recorder stops and restarts between successive data blocks during which time the tape moves at a variable speed, and no data can be recorded. This results in a gap between data blocks. The gap length is strictly a tape transport characteristic and depends upon tape speed, start time, and stop time of the transport. It is, therefore, desirable to design the tape recorder for generating short gaps. It is also desirable to use buffers with sufficient storage capacity to yield data blocks which are long compared to the gap length in order to achieve good tape utilization.

For the tape recorder described in this article, the gap length is approximately 1.27 cm (0.5 in.)[1] at a tape speed of 17.78 cm/s (7 in./s). If a linear recording density of 1575 bits/cm (4000 bits/in.) and single track recording is assumed, a pair of 8096-bit buffers would generate data blocks of 5.08 cm (2 in.). This would result in 80% of the magnetic tape being used for data recording.

[1]Where applicable, the International System of Units is stated first, followed by the customary units in parentheses. In each case, the value in parentheses represents the measured or calculated unit.

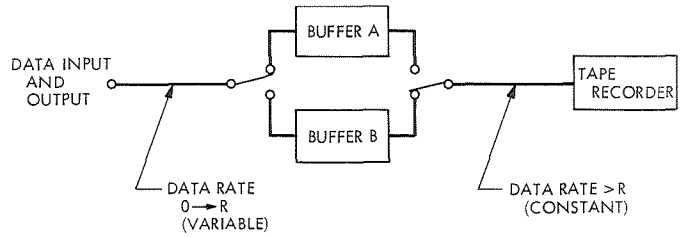

Figure 1. Data storage system

Tape Transport

The most important design requirements for the tape transport are high reliability and long life. This implies that a transport can never employ components that are basically unreliable or subject to considerable wear. Any mechanical system, however, must be satisfied with components having at least some wear and limited reliability. It is concluded, therefore, that all components and materials which are subject to wear, fatigue, or chemical instability should be known to function for 12 yr with some acceptable probability of success. Furthermore, their number should be reduced to the bare minimum.

From these rather general design rules, a number of more specific postulates can be derived:

(1) The transport mechanism shall be as simple as possible. It shall be stripped of all non-essential functions or components.

(2) Since there is no known way to construct a tape transport without bearings (which are subject to wear and fatigue), their number shall be minimized, and they shall be selected for minimum wear and fatigue. Ball bearings are generally considered most desirable for tape recorders. Their wear can be reduced to negligible values if operated at very low speed and load and assured lubrication. Material fatigue is also negligible if they are sufficiently oversized. Proper lubrication can be assured for long periods by using grease instead of oil. Again, large bearings will hold larger quantities of lubricant, and slow speed will stretch out the aging process of the lubricant.

(3) A tachometer is not an essential component and shall not be used. Playback of a prerecorded control frequency on the tape will more reliably generate a speed signal.

(4) Drive belts commonly used in tape transports can fatigue and break. There is not enough data available today to assure that belts can maintain the necessary tension over a period of 12 yr. Drive belts, therefore, shall not be used.

(5) The oxide surface of the magnetic tape should not be in sliding contact with any solid surface to minimize tape wear. If this is not possible, the total surface area sliding against the oxide and the contact pressures involved shall be minimized.

(6) Magnetic tape shall be handled as gently as possible. It, therefore, shall be guided along as few devices as possible and it shall not be wound tightly on a reel.

(7) The number of non-metallic substances shall be minimized and the chemical stability and compatibility of all materials inside the transport package shall be carefully verified.

(8) The number of connector pins feeding through the transport package shall be minimized because connector feedthroughs present a sealing hazard. This suggests incorporating part of the electronics inside the transport package, especially for multichannel recorders. All electronic components inside the transport shall be enclosed in hermetically sealed metal containers to prevent contamination of the transport by outgassing products from electronic components.

In order to satisfy Postulates 1 and 6, a coplanar reel-to-reel transport configuration is most promising. Figure 2 shows a very simple configuration. It consists of two motors with reels and tape packs on each motor shaft. It also uses two stationary tape guides, which do not touch the oxide, and a set of recording heads. All components are mounted on a precision plate.

The magnetic tape is fastened to the reel hubs. The take-up reel motor pulls the tape and winds it on its reel. The supply-reel motor

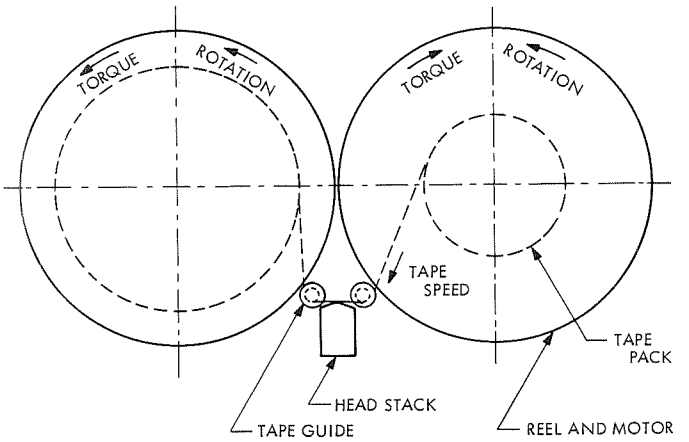

Figure 2. Two-motor tape transport

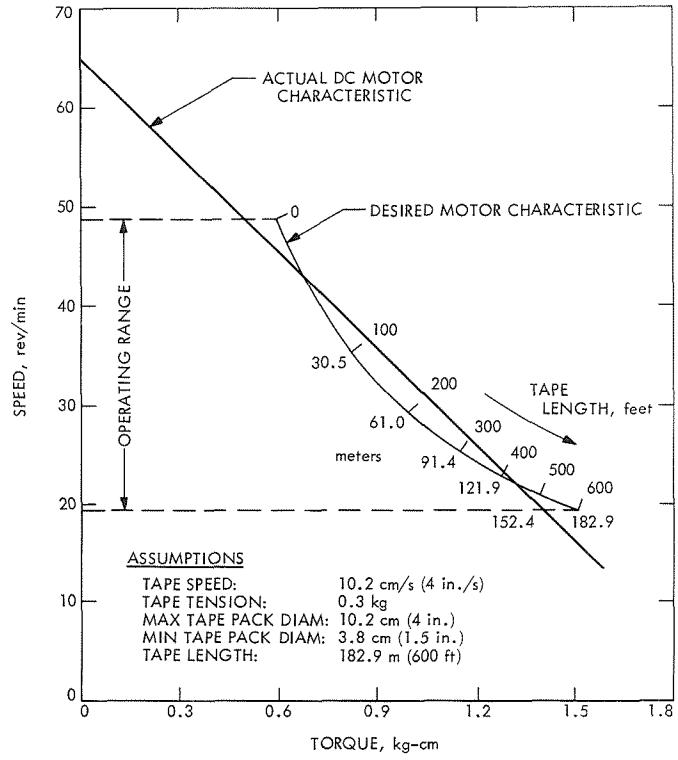

Figure 3. Take-up reel drive

develops torque in the direction opposite to the tape motion. It, therefore, pulls back on the tape, generating tape tension. While the take-up reel motor generates tape speed, the supply-reel motor provides for the necessary tape tension. The transport is symmetrical and, therefore, can drive the tape in both directions equally well. Tape speed reversal is obtained by interchanging the functions of the two motors.

During normal operation the tape speed has to be precisely constant. Since the tape pack diameter on the take-up reel changes constantly, the take-up motor speed will change throughout a tape pass. At the beginning of a tape pass, the tape pack is small and motor speed has to be high. For the same reason, motor torque is low if constant tape tension is assumed. As more tape is wound on the reel, motor speed will decrease and torque increase. Figure 3 shows the desired motor speed as a function of motor torque at constant tape tension. This hyperbolic function can be nicely approximated by the proper design of a dc motor and fine trimming with a series resistor to the motor. The take-up reel motor therefore will automatically generate approximately constant tape speed if constant tape tension is provided. Conversely, if the tape speed is held constant, tape tension will deviate from the nominal values only by a small amount.

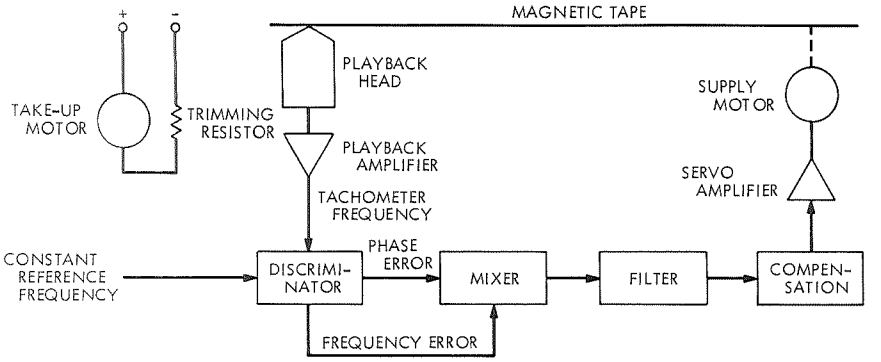

Figure 4. Drive electronics for two-motor tape transport

The supply motor generates tape tension and is being servo-controlled to regulate the tape tension in such a way that constant tape speed results. This is being done with a phase-lock servo, which compares a voltage derived from the tape with the voltage output of a stable oscillator. The tape signal is pre-recorded on a precision laboratory recorder on one track over the full length of tape. The tape recorder itself has only playback capability on this track. The frequency derived from this track is directly proportional to the tape speed.

The phase-lock servo has two feedback loops, as shown in Figure 4. One loop generates an error signal proportional to the difference of the frequencies of the two voltages. This error signal is filtered and amplified and will subsequently be used to drive the supply motor. It will regulate motor current in such a manner as to cause the tape frequency to become approximately equal to the stable reference frequency. A second feedback loop will generate an error signal proportional to the phase difference between the two voltages. Its error signal will take over the job of regulating the motor current after the first loop has brought the tape frequency within capture range of the second loop.

This double-loop servo will feed just enough electrical power into the supply motor to cause tape speed to be precisely constant at all times. The speed is determined by the external reference frequency and the density at which the tape frequency has been recorded.

A very important feature of this tape transport is the fact that the tape tension will disappear as soon as the recorder is turned off. This is very desirable because it will prevent tape-to-head stiction during prolonged periods of inoperativeness. However, the tape has to be prevented from falling off the tape guides or throwing a loop. For this purpose, the tape reels contain flanges which are more precise than for most other tape recorders. The tape is allowed to fall down on the flanges after the recorder has been turned off. Throwing a loop is prevented by using a

magnetic brake in each motor. The motors, always running at slow speed, will be stopped by the brake in a very short time.

The brake consists of a powerful permanent magnet and a weak permanent magnet which is magnetized by the powerful magnet. As one magnet rotates and the other remains stationary, the weak magnet is continually re-magnetized by the powerful magnet. This causes high hysteresis losses because the coercivity is not negligible. These losses result in a drag torque which opposes the rotation and can be made constant in the time and speed domain. Past experience indicates the required brake torque will be on the order of 0.07 to 0.36 kg-cm (1 to 5 oz-in.), depending upon the reel diameter. In a practical motor, the powerful magnet is identical with the dc motor magnet and the weak magnet takes the place of the soft iron yoke ring. Therefore, the braking action is obtained by simply selecting a proper magnetic material for the yoke ring. No geometric changes of the motor design are required.

In order to obtain good damping characteristics, the motor is designed with relatively high brake torque. This generates more tape tension than desired. The brake torque of the supply motor must therefore be reduced by driving the motor in the direction of the tape travel with very little torque. Referring again to Figure 4, the double-loop servo generates an error signal that is amplified to drive the supply motor. The servo amplifier is biased so as to drive the supply motor with low torque in the direction of tape travel if the error signal is zero. If the tachometer frequency begins to fall below the stable reference frequency, a positive error signal is generated and drives the supply motor with more torque. As the supply motor generates more torque against the brake, the pull on the tape will be relaxed somewhat, which allows the free running take-up motor to accelerate and increase the tachometer frequency. Tape speed is thus stabilized by regulating the net shaft torque of the braked supply motor.

As mentioned before, the tape transport will be operated in a start/stop mode. Because both motors run at very slow speeds and exhibit a substantial drag torque, the tape transport stops very fast. It also starts very fast because of the high starting torque of the dc motor.

The general reliability and operating life of an incrementally operated tape transport is often questioned. Increased wear of bearings, tape, and heads is claimed. This may be true to some degree. Several years ago, JPL developed an incremental tape recorder (Reference 2) which was subjected to extensive life testing at high repetition rates. This machine accumulated approximately 10^9 start/stop cycles before it was finally put in storage. No bearing, head, or tape load was ever exchanged. This test

did not preclude the possibility of accelerated wear within an incrementally operated tape transport, but showed that a properly designed machine can perform a large number of start/stop cycles.

The motors of the tape transport of Figure 2 run in the vicinity of 100 rev/min for a typical space application. If operated continuously for 1 yr at 100 rev/min, a bearing will accumulate approximately 50 million revolutions. With proper lubrication this will not wear out an originally healthy bearing. It is not clear, however, if proper lubrication is assured during a stop/start transition. Some degradation of the lubricating process must be assumed. Measurements of electrical current conductivity between inner and outer race ways of ball bearings indicate that some separation of the metallic surfaces is accomplished even when the bearing is stopped. This leads to the conclusion that at least some lubrication occurs all through the stop/start cycle.

Concluding Remarks

The tape recorder described in this article is currently being developed for future outer-planet missions. A feasibility model has been built and operated successfully for more than 1000 h without failure.

References

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